INVESTIGATION OF SPHEROMAK CONFIGURATION GENERATED
BY INDUCTIVE METHODS IN THE S-1 DEVICE

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ABSTRACT

This paper summarizes the characteristics of the spheromak plasmas obtained during the past five-year operation period of S-1 experiments. The S-1 Spheromak device, which began operation in 1983, generates a compact toroid in which the self-generated toroidal field in the plasma is comparable to the poloidal field. The S-1 experiment is unique in that spheromak plasmas are formed by inductive transfer of magnetic flux from a toroidal-shaped "flux core", and plasma stability is maintained by shaping of the externally applied equilibrium field and using loose-fitting passive conductors. Without stabilizer coils, the plasma was unstable to gross MHD modes, with the tilt or shift being dominant. Significant improvements in plasma stability and parameters occurred after the installation of passive Figure-8 stabilization coils or funnel-shaped conductor plates. Stable spheromaks with up to 550 kA

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toroidal current have been obtained. The lifetime of the stable spheromak configuration has exceeded 1 msec with the magnetic field decay time, $\tau_B = B/(dB/dt)^{-1}$, varying from 0.5 to 2 msec. The major radius of the plasma was in the range 0.4 to 0.65 m and the minor radius was in the range 0.25 to 0.45 m. With the improved reproducibility of the discharges with passive stabilizers, a detailed MHD analysis was carried out with magnetic probes both inside and outside the plasma. It was found that relaxation to the Taylor (minimum-energy, force-free) state was an important mechanism in S-1 spheromak formation. Two-dimensional spatial profiles of $u = \vec{j} \cdot \vec{B}/B^2$, where $\vec{\nabla} \times \vec{B} = u\vec{B}$ for a force-free state, have been deduced from internal probe data to verify the Taylor state ($u = \text{constant}$). Magnetic fluctuations with toroidal mode numbers $n = 4, 3, 2$ have been identified to be associated with the attainment of a Taylor state during formation, and are presumed to allow a conversion of poloidal to toroidal flux, or toroidal to poloidal flux, to occur.

The most important objective for the S-1 experiment is to investigate the confinement feature of the spheromak configuration. With a rather extensive diagnostic system for this size device, the transport characteristics of the S-1 spheromak have been measured for plasmas with $10 \leq T_e \leq 130$ eV and $2 \leq n_e \leq 15 \times 10^{13} \text{ cm}^{-3}$. The scaling of electron temperature T_e and density n_e with plasma current density has been obtained in a wide operation regime. The most important finding is that the peak electron pressure scales as $n_{e0}T_{e0} \propto j_0^2$ ($j_0 = \text{peak toroidal current density}$) with $T_{e0} \propto j_0^2$ and $n_{e0} = \text{constant}$. These scaling results, which are similar to those obtained in the reversed-field pinch device, suggest that $\beta = \text{constant}$. Energy and particle confinement times are determined.

In high temperature spheromaks, the mechanism of "sawtooth-type" relaxation events often observed is made clear by measuring 2-D magnetic field contours and radial electron temperature profiles. The large resistive loss

at the plasma edge is responsible for the deviation of the plasma configuration from the Taylor state. When the magnetic configuration departs far from the Taylor state, it becomes unstable to low n (n = toroidal mode number) ideal MHD modes. Through these instabilities, magnetic reconnections take place (relaxation) and a Taylor state is recovered. It is found that the confinement time of spheromak plasmas is significantly affected by this relaxation phenomena.

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1. INTRODUCTION

The spheromak is a compact toroidal magnetic configuration for confinement of plasmas. Poloidal fields are produced by plasma currents and external coils. Toroidal fields are produced entirely by plasma currents so that no coils link the plasma [1,2]. These are attractive features for the design of fusion reactors and add flexibility by permitting translation and compression of the plasmas [3]. Furthermore, the requirement for auxiliary heating is reduced because of the high level of joule heating associated with the large plasma currents, and a reactor design can be conceived based entirely on ohmic heating.

Two conceptual spheromaks are shown in Fig. 1. Figure 1(a) depicts a classical spheromak configuration whose analytical description was first given by Lust and Schlüter [4]. Figure 1(b) represents a spheromak with a "current hole" in which the outer plasma section does not carry current. In the configuration shown in Fig. 1(b), the magnetic shear becomes strong at the plasma edge and the plasma is considered to be more stable against ideal MHD modes [5-7].

The spheromak has many features in common with the Reverse Field toroidal Pinch [8] (RFP) including shear stabilization dynamics and, possibly, confinement. The most notable difference between the RFP and the spheromak is that the spheromak does not have a reversal of the toroidal field at the outer edge of the plasma, thus making the spheromak equilibrium possible without the use of toroidal field coils or a close-fitting conducting shell. One of the important tasks of the present S-1 spheromak research [9] is to investigate if and how MHD stability and favorable confinement are maintained without close-fitting conducting shells like those in the RFP. In the past several years, significant progress has been made in understanding the spheromak configuration [10].

One of several approaches [11-15] to produce spheromaks, the S-1 Experiment [16] was designed to investigate an (electrodeless) inductive technique of forming the spheromak [15] by transferring poloidal and toroidal flux to the plasma from a flux core and to study the confinement properties of spheromaks. When the poloidal- and toroidal-coil currents in the S-1 flux core are pulsed, the forming plasma approaches the minimum-energy state theorized by J. B. Taylor [17] and a spheromak configuration is created. Typical parameters are major radius of 40-65 cm, minor radius of 25-45 cm, toroidal plasma currents of 200-550 kA, and toroidal magnetic fields of 2-3 kG.

Without stabilizing conductors, the plasma was unstable to gross MHD instabilities which are the (nearly) rigid-body $n = 1$ tilt and shift modes and the $n = 0$ axial translation mode [18]. The $n = 0$ instability has been stabilized by appropriate shaping of the equilibrium field. A significant improvement in plasma stability and parameters occurred with the installation of passive Figure-8 stabilization coils [9,19,20]. The stable lifetime of the spheromak configuration exceeded 1 msec and a magnetic field decay time, $\tau_B = B/(dB/dt)^{-1}$, as high as 2 msec has been obtained.

With the improved reproducibility of the discharges, a detailed MHD analysis was carried out with magnetic probes both inside and outside the plasma. It was found that relaxation to the Taylor (force-free, minimum energy) state was an important mechanism for S-1 spheromak formation [21]. Two-dimensional spatial profiles of $\mu = \vec{j} \cdot \vec{B}/B^2$, where $\nabla \times \vec{B} = \mu \vec{B}$ for a force-free state, have been deduced from internal probe data to verify the Taylor state ($\mu = \text{constant}$) [22]. Magnetic fluctuations with toroidal mode numbers $n = 4, 3, 2$ have been identified [23] and conjectured to be responsible for the attainment of a Taylor state during formation by allowing a conversion of poloidal to toroidal flux, or vice versa, to occur [21,24].

The electron temperature T_e ranges from 10 to 130 eV depending on plasma current and fill pressure. The electron density n_e reaches peak values of $(0.2 \text{ to } 1.5) \times 10^{14} \text{ cm}^{-3}$ during the formation phase and decays thereafter with a time constant of about 1 msec. The volume-averaged beta, β , is in the range of 5-10%. The major objective of the recent experiments in S-1 has been the investigation of transport characteristics of the spheromak configuration. The scalings of electron temperature and density have been determined and the particle and energy confinement times are now investigated over a wide operating range. The most important finding is that the peak electron pressure scales as $n_{e0}T_{e0} \propto j_0^2$ (j_0 = peak toroidal current density) with $T_e \propto j_0^2$ and $n_{e0} = \text{constant}$. The experimental results are analyzed in terms of a simple power balance code. The present scaling result suggests $\beta = \text{constant}$ for optimized plasma parameters and is similar to that obtained in some RFP devices.

In Sec. 2, the S-1 device and its major components are described, together with a brief description of the diagnostic systems. Section 3 describes the experimental investigation of the S-1 formation scheme. Section 4 contains a description of operation with the Figure-8 coils. Section 5 presents a study of the equilibrium of the S-1 spheromak configuration which is characterized by the Taylor state. In Sec. 6, flux conversion phenomena and magnetic fluctuations are closely examined. Deviations of the spheromak configuration from the Taylor state and relaxation phenomena which take it back to the Taylor state are discussed. Section 7 contains a summary of the transport characteristics of S-1 spheromak plasmas together with results from some recently installed diagnostic systems. In Sec. 8, discussion and some considerations for future research are presented.

2. THE S-1 DEVICE AND DIAGNOSTIC SYSTEMS

2.1 Major Components of the S-1 Device

A cross section of the S-1 device (without passive stabilizers) is schematically presented in Fig. 2. A photo of the S-1 device is shown in Fig. 3. The major components of the S-1 device are the flux core, vacuum vessel, equilibrium field coils, and power supplies [25]. The major and minor radii of the flux core are 1 m and 0.19 m, respectively. The flux core contains pulsed poloidal-field (PF) coils, pulsed toroidal-field (TF) coils, and quasi-steady-state poloidal-field [equilibrium field (EF)] coils. The core is covered by a thin Inconel liner that serves as a low-outgassing vacuum surface with a relatively low yield from plasma sputtering. The flux core liner was made sufficiently resistive with a thickness of ~ 0.25 mm so that the flux can penetrate in ≤ 1 μ s. In order to fabricate this liner, Inconel sheets about 2.25-mm thick were fabricated by explosive forming to make two "half-toroids" and chemically milled to reduce the thickness. After machining to size, the liner halves were welded in place on the flux core and the space between the liner and the core was filled with urethane. The completed flux core mounted in the center section of the vacuum vessel is shown in Fig. 4.

The PF and TF circuits each use a capacitor bank of voltage $V \leq 20$ kV for energy storage, with more than 1/2 MJ in each bank. The quasi-steady-state equilibrium field (EF) is produced by a set of coils mounted on the vacuum vessel, and the additional two-turn coil inside the flux core. The shape of the equilibrium field can be varied by connecting the EF coils in various combinations to achieve indices of field curvature [$n = (-R/B)(dB/dR)$] at $R = 0.55$ m of $n = -0.2, -0.06, +0.1, +0.8$, and $+0.7$. Two DC motorgenerators power the EF coils.

A digital system based on LSI-11/23 computers controls all aspects of the device operation. A serial highway links the various subsystem CAMAC

diagnostic crates distributed around the device. Fiber optic transmission lines connect the CAMAC crates and distribute the synchronized clock signals. The CAMAC crates and the control room are shielded to reduce electromagnetic interference.

The stainless steel vacuum vessel consists of two domes and a center section. The domes are commercially available pressure vessel components that are further machined. The flux core is mounted in the center section. Two 1000 torr 1/sec turbo molecular pumps are the principal vacuum pumps. Additional pumping is provided by titanium gettering the walls and by use of two 1000 torr 1/sec cryo pumps. Vacuum vessel conditioning is done by DC glow discharge cleaning. The base pressure inside the vessel is in the range of 2×10^{-8} to 2×10^{-7} torr. For plasma generation, a precisely controlled pulsed gas of $\approx (2 - 10)$ mtorr is injected by piezo-electric valves seconds before a discharge.

2.2 Diagnostics

The S-1 device is equipped with the following diagnostics: external and internal magnetic probes, flux loops, Rogowski coils, two Thomson scattering systems (multipoint and single point), single channel CO₂ laser interferometer, multichord visible and vacuum UV spectroscopic systems, bolometers, triple Langmuir probes, an ultra-soft x-ray pin-hole camera, framing camera, and a quadrupole residual gas analyzer. These diagnostics installed on the S-1 device are pictured schematically in Fig. 5.

2.2.1 Magnetics

The magnetic configuration of the S-1 spheromak was thoroughly studied using both internal and external magnetic probes, Rogowski coils, and flux loops.

The internal measurements were made with magnetic probes inserted into the plasma which limited these measurements to plasmas with electron temperatures of ≤ 80 eV. The probe was comprised of 15 sets of coils inside a straight thin-walled metal tube. Each set consisted of three coils to measure the magnetic field in the major radius direction (B_R), the toroidal direction (B_ϕ), and the z-direction parallel to the major axis (B_z). These coils have a diameter of approximately 0.6 cm. The probe, extending outward in major radius from the major axis of the device to $R = 80$ cm, was supported by a boom that moves along the machine axis (see Fig. 5). The time evolution of a magnetic field profile in major radius, R , can be obtained during a single discharge for fixed z and ϕ . The data are first integrated in time and then digitized and recorded with respect to time by the computer data acquisition system. The magnetic probe data can then be analyzed to obtain important quantities such as poloidal flux Ψ , poloidal current RB_ϕ , current density j , $\mu = j \cdot B/B^2$, toroidal current I , and toroidal flux Φ . An (average-field) two-dimensional cross section of the plasma in a chosen R - z plane can be obtained by moving this probe between discharges, in the z -direction. To construct a two-dimensional plot (of poloidal flux, for example), data from approximately 40 consecutive and reproducible discharges is required. These data yield a (R, z, t) data array with spatial mesh size of 7.5 - 15 cm. The required reproducibility was made possible by the installation of Figure-8 coils [9,20] which helped stabilize the $n = 1$ shift mode during the discharge. The probe was also rotated toroidally to examine the axisymmetry of the fields.

The time evolution of the total toroidal plasma current and magnetic flux in the plasma for each discharge could be measured by sets of Rogowski coils and flux loops outside of the plasma. Similarly, a flux loop running

the long way around the flux core could measure the total poloidal flux linking the flux core, which is a useful measure of how detached a plasma is from the flux core.

The toroidal variation of the magnetic field was monitored by an array of coils (N-probe shown in Fig. 5). This system can detect the axisymmetric evolution of the discharge, and also any $n = 1$ tilt and shift modes and higher n -number coherent modes [where n is defined by the functional dependence $\exp(in\phi)$ of the magnetic fluctuations on toroidal angle ϕ]. The N-probe diagnostic coil array consists of sixteen pairs of coils distributed toroidally inside the S-1 vacuum vessel at a major radius of 50 cm and an axial position of 60 cm to measure major radius and toroidal components B_R and B_ϕ , respectively. The coils were located just outside the Figure-8 coil system [see Sec. 4.1] which was, in turn, outside the separatrix of the spheromak. The dB/dt data from the N-probe are digitally integrated to obtain $B(\phi, t)$ which is then resolved into modes by use of a discrete spatial Fourier transformation.

2.2.2 Electron Temperature T_e and Density n_e

Electron temperature and density measurements have been made using a single point Thomson scattering system [26] and a multipoint Thomson scattering system [27]. For the single point Thomson scattering diagnostic, a 15-joule ruby-laser beam is focused into the plasma at one of several positions in the midplane along the major radius. Scattered light is collected by a 20-cm lens and imaged onto a fiber optic bundle which transmits the light to an 8-channel polychromator. The signals are digitized and recorded by two LeCroy 2249A ADC's in parallel. The first ADC is gated on

during the arrival of the scattered light signal, while the second unit is gated on for 150 ns after the signal in order to subtract the background plasma light.

The electron temperature and density profiles were measured by a multipoint Thomson scattering diagnostic [27]. The viewing geometry cuts across the midplane at an angle of 25° as shown in Fig. 5. The scattered light is collected by an f lens and imaged onto a fiber-optic bundle which views a 72-cm chord and transmits the light to a spectrometer. The dispersed light from the spectrometer is imaged onto a multi-anode microchannel plate detector (MCP). The MCP has a 10×10 array of anodes to collect the amplified current. This results in two sets of data, each with ten spatial times ten spectral channels. The first set integrates at the time of the laser signal and the second set about 50 ns later to measure the background plasma light.

A triple Langmuir probe [28] was used to monitor the electron temperature and density of the edge plasma as a function of time. The probe consists of a double Langmuir probe biased to collect the ion saturation current, and a third tip to measure the floating potential of the plasma. The voltage difference between the more positive tip of the double probe and the third tip is proportional to the electron temperature, and the ion saturation current can be used to determine the electron density. At high electron temperatures ($T_e > 35$ eV), uncertainties in the measurement due to probe arcing limited its use. Density calibration was done both by Thomson scattering systems which give an absolute number for n_e and by comparing measured density profiles with the line-averaged density from CO_2 laser interferometry.

2.2.3 Line-Averaged Density $\bar{n}_e$

The line-averaged electron density was measured along the z-direction (perpendicular to the midplane) at a specific major radius of $R = 40$ cm using a CO_2 quadrature interferometer from which both the sine and cosine of the phase shift could be obtained. Data were recorded at a 1-MHz digitization rate. The density is determined from calculating the phase shift, which is a function of the index of refraction.

2.2.4 Spectroscopy and Radiation

In addition to the magnetic diagnostics, the positional stability and MHD properties were studied using a framing camera and an ultra-soft (>10 eV) x-ray pinhole camera. The x-ray detection system provides time-resolved emissivity profiles from an array comprised of 19 silicon surface-barrier detectors which view nearly perpendicularly to the midplane at different major radii distances from the device axis. Various high-energy band-pass filters such as H_α , glass, fused silica, MgF_2 , and several thin metallic filters (with cutoffs at 100, 150, 200, 350, and 600 eV) are used to identify the energy spectrum.

To investigate impurities and their degree of ionization, two near-ultraviolet/visible range (2000-8000 Å) monochromators were installed on S-1. Each is a Czerny-Turner grating instrument with a 1200 g/mm grating and a CsSb photomultiplier tube with quartz envelope. A resolution of 0.5 Å is attainable.

To make a quantitative estimate of impurity line radiations in the vacuum ultraviolet region, a 1-m grazing incidence spectrographic monochromator, GISMO [29], was installed on S-1. It is equipped with a 2400-g/mm grating at an 85° angle of incidence and is a two-channel detection

system with Bendix magnetic electron multipliers. A near-UV/visible Czerny-Turner monochromator was used for an absolute calibration of the GISMO system.

A platinum bolometer was installed to monitor the time-integrated radiated power from the plasma. With a time response of 1 msec and a cooling time of 100 msec, the resistance of the platinum foil is sampled before and after the discharge to determine the total absorbed energy per discharge. The bolometer is mounted on the end plate of the S-1 vacuum vessel at a distance of 55 cm from the symmetry axis of the device. The solid angle viewed is 0.019 steradians, so that the field of view at the midplane includes from $R = 45$ to $R = 65$ cm. The energy deposited due to charged particles hitting the detector is negligible because the magnetic field curvature is large enough at the detector housing to block charged particles from passing through the collimating baffles to the detector. Furthermore, the neutral and charge-exchange mean-free paths are short enough (2 cm) to ensure that any charge-exchanged ions or neutrals will be thermalized before striking the detector. The detector has been calibrated based on the resistivity and thermal capacity of platinum.

A single-channel lithium tantalate pyroelectric detector was used to provide information on the time dependence of the total radiated power emitted by the plasma.

3. INDUCTIVE FORMATION OF SPHEROMAKS

3.1 Formation Sequence

Two important characteristics of S-1 experiments are 1) inductive formation (as opposed to reliance on electrodes) and 2) stabilization of the spheromak against rigid-body $n = 1$ instabilities by use of loose-fitting conductors and coils (as opposed to, for example, a close-fitting

flux-conserver wall)). In S-1 experiments, formation of spheromaks occurs on a time scale much longer than τ_A ($\tau_{\text{form}} \geq 10^3 \tau_A$), where τ_A is the Alfvén time; therefore, it is called a slow formation.

To form a spheromak plasma in S-1, the currents from the toroidal- and poloidal-field power supplies are programmed to induce poloidal and toroidal plasma currents simultaneously, so that the magnetic configuration approaches that of a force-free, minimum-energy (Taylor) state. The formation scenario [15] can be described with reference to Fig. 6. Initially, a steady-state equilibrium field is generated to support the final plasma equilibrium. A poloidal field generated by a toroidal current inside the flux core is pulsed on. The superposition of these two fields creates a field weaker on the small-major-radius side of the core than on the large-major radius side. A toroidal solenoid inside the core is then pulsed on at time $t = 0$. Fortunately, the poloidal electric field created around the core is sufficient to break down the neutral gas into a plasma; otherwise, other plasma initiation methods would be required. Electron cyclotron resonance ionization was used to initiate the plasma, but no significant difference in formation was observed. The increasing toroidal flux in the toroidal solenoid induces a poloidal current in a toroidally concentric plasma surrounding the core. Simultaneously the toroidal current in the core is reduced to induce a toroidal current in the plasma. The $\vec{j} \times \vec{B}$ forces stretch the plasma towards the device axis where the poloidal field is weakest and reconnection of poloidal magnetic field lines then occurs which results in the creation of a plasma toroid, the desired spheromak configuration.

3.2 Operation Without Stabilization Coils

In the early phase of S-1 operations when no additional stabilizer coils were used, two representative discharge modes were investigated: the

"detached" discharge mode, in which the spheromak plasma completely pinches off (detaches) from the flux core, and the "linked" discharge mode, in which outer flux lines remain linked around the flux core after the formation phase. The flux core is outside the separatrix after formation is complete in detached discharges while it is inside the separatrix for linked discharges. In detached discharges, the PF circuit is crowbarred after the plasma detaches from the core. In linked discharges, the PF circuit is crowbarred before the plasma completely detaches from the core.

In the absence of stabilizing conductors, a detached spheromak plasma is predicted to be unstable to at least one of the gross MHD modes (tilt, shift, or axial translation) in any type of external equilibrium field [1,7]. Experimentally, detached spheromaks are found to be unstable against gross MHD modes [9,20], in agreement with theory. For equilibrium fields with large positive values of the index of field curvature, data from magnetic probes and framing camera show that the spheromak shifts soon (within 0.1 msec) after formation is complete [9]. A shift is defined as a translation in a direction parallel to the midplane. The shift velocity is measured to be in the range of $(0.5 - 1.0) \times 10^6$ cm/sec. The direction of the shift motion is observed to be random and is considered to be related to slight nonuniformities during formation.

For linked discharges, the formed spheromak is observed to maintain a stable equilibrium for a longer time. A typical spheromak configuration appears 0.2 msec after the plasma is initiated and lasts more than 0.5 msec (Fig. 7). Without a passive stabilizer it is necessary to keep a large fraction (50 - 90%) of the spheromak's poloidal flux linked to the flux core or line-tied to vacuum vessel walls to prevent loss of positional stability. In these linked discharges, electron densities range from (0.2 to $2) \times 10^{14}$ cm⁻³ for H₂ and H_e fill pressures of 1-10 mtorr. Peak electron

temperatures of 15 eV - 45 eV were measured (discharge average 25 eV) for $I \leq 200$ kA by the single-point Thomson scattering system. The observed low temperature was attributed to low current density ($I/N < 1 \times 10^{-4}$ A·m, $N = \pi a_p^2 \bar{n}_e$), oxygen impurity radiation, and parallel electron convection losses.

3.3 Injection of Magnetic Helicity in S-1 Formation

Helicity is a useful concept for understanding the formation (and sustainment) of a spheromak configuration. The formation can be considered in terms of an injection of magnetic helicity from the flux core into the plasma.

The helicity in a spheromak configuration can be written as

$$K \equiv \int_{V_{\text{plasma}}} \vec{A} \cdot \vec{B} \, dV = \alpha \Phi^2, \quad (3.1)$$

where Φ is the total toroidal flux of the plasma and α is a constant for a given size and shape configuration. The rate of injection of magnetic helicity into the plasma from the flux core is [30,31]

$$\dot{K}_{\text{in}} = 2 \Psi_{\text{core}} \dot{\Phi}_{\text{core}}, \quad (3.2)$$

where Ψ_{core} is the poloidal flux linking the flux core and Φ_{core} is the toroidal flux inside the flux core. Integrating with respect to time yields

$$K_{\text{in}} = \int_0^t 2 \Psi_{\text{core}} \dot{\Phi}_{\text{core}} \, dt. \quad (3.3)$$

The helicity input to the plasma, K_{in} , can be compared to the measured helicity in the final spheromak (Eq. 3.1) to estimate the efficiency of formation. The helicity in the final spheromak was compared to the injected

helicity produced by a wide range of voltages on the poloidal- and toroidal-field capacitor banks. The global magnetic helicity in the plasma after formation was proportional to that injected by the applied currents in the flux core, regardless of how that helicity was produced by those currents.

4. IMPROVED STABILITY IN S-1 SPHEROMAKS WITH PASSIVE STABILIZING CONDUCTORS

4.1 Stabilization of Tilt and Shift Modes Using Figure-8 Coils

In order to stabilize the gross MHD modes, a passive Figure-8 stabilization coil system was designed based on earlier theoretical studies and Proto S-1 experimental results [18,20,30]. The name of the coil is derived from its shape, which is in turn based on the eddy current path which would be induced in a spherical conducting wall if one were placed around a tilting or shifting spheromak plasma. The installation of the Figure-8 coils in S-1 made a dramatic improvement in both the gross MHD stability and the quality of the formed spheromak plasmas. With this stabilizing system, an almost completely detached spheromak can be kept in a stable equilibrium for one millisecond, an order of magnitude improvement in the duration of the stable quiescent period.

The strategy behind the first attempt to obtain grossly stable spheromaks was to operate with a shift-unstable equilibrium field and then to provide shift stability with a set of Figure-8 coils optimized for such an instability assuming the major radius of the spheromak to be $R = 45 - 65$ cm. As shown in Fig. 8, two Figure-8 coils were installed on each side of the midplane of the flux core with the cross points of the coils at 60 cm ($\approx 1.5 a_{\text{plasma}}$) away from the midplane. The outermost radius of the Figure-8 coil is 75 cm. The present coils were made of 2 cm $\times$ 3 cm cross section oxygen-free copper bars.

Figures 9(a) and 9(b) show the time evolution of the radial profiles, on the midplane, of the B_z field (z-component of the poloidal field, where the z-axis is the symmetry axis of the device) and the B_t field (toroidal field) for a plasma discharge without the Figure-8 system. Immediately after the plasma is formed, it starts shifting in the $z = 0$ plane with a speed of $2 - 5 \times 10^5$ cm/sec. Figures 9(c) and 9(d) show the corresponding fields for a plasma discharge with the Figure-8 system installed, all other parameters remaining the same. The spheromak is now kept in a stable equilibrium position for more than a half millisecond. With this Figure-8 coil system, gross MHD stable spheromaks have been obtained with more than 85% of the poloidal flux detached from the flux core; with the present set-up, if the plasma pinched off completely from the core, the plasma edge also departs from the coils and the passive stabilization becomes ineffective.

The gross stability of the plasma formation and decay afforded by the Figure-8 coils also provided the necessary reproducibility to map the two-dimensional profiles of the magnetic field structure using data compiled from many discharges. Figure 10 presents a time evolution of poloidal flux and poloidal current contour plots taken 0.2, 0.3, 0.4, and 0.5 msec after the start of the discharge. An excellent match of the poloidal flux Ψ with the poloidal current RB_t confirms the low β spheromak equilibrium during the entire period.

4.2 Completely Detached Plasma Using Funnel-Shaped Conductors

An alternative passive stabilizing conductor system was tested in S-1. This consisted of a pair of funnel-shaped copper conductors placed near the separatrix null points of the S-1 spheromak configuration as shown in

Fig. 11. Each funnel had four radial slots in it to prevent large toroidal currents from being induced during formation. The eddy current time constant of the funnel was greater than 5 msec.

These stabilizers provided two functions: First, to stabilize the spheromak plasmas against the gross MHD modes, even with the plasma completely pinched off from the core. Figure 12 presents experimentally measured two-dimensional poloidal flux plots, assuming $j_t = 0$ at the funnel surfaces. (In the experiment, the total current that flows in the funnel is measured to be small.) The funnels provided the capability to detach fully the spheromaks from the flux core without encountering tilt or shift instabilities. The second major function of the funnels is to increase the plasma current density by allowing the plasma to be compressed towards the funnels. For similar operation parameters, the current density could be raised from 100 A/cm² without funnels to 170 A/cm² with funnels.

4.3 Improvements in Plasma Characteristics With the Figure-8 Coils

Figure 13 contrasts data from discharges with and without passive Figure-8 stabilization coils which were collected under similar conditions within a two-week period. The first four rows summarize the spectroscopic data obtained with visible monochromators. The emission due to metals (Fe, Ni, Ta) ejected from the walls was substantially reduced after the stabilizing coils were installed. Copper emission appears with installation of the coils, as expected, but after the collapse of the spheromak configuration. H₂ emission is quantitatively similar for both cases although the fluctuation level is noticeably reduced with Figure-8 coils. A Rogowski coil was used to monitor current conducted along the open field lines which, for certain equilibrium field shapes, intersected the wall. One can see a dramatic

decrease in the magnitude of this current after Figure-8 installation, which, consistent with the above-mentioned spectroscopic data, indicates a reduction in the interaction of the plasma with the wall.

As described earlier, magnetic field pickup coils were used to monitor the toroidal field inside the plasma. The data show that the spheromak configuration is maintained for a substantially longer time after the stabilizing coils were installed. Also, Thomson scattering at $R = 45$ cm, $z = 0$ indicates a corresponding increase in the electron temperature. Before the installation of the Figure-8 coils, the shot-averaged electron temperature was 25 eV and the electron density was observed to decay rapidly. For optimized plasma discharges with the Figure-8 coils, the average electron temperature increased to 50-70 eV.

5. S-1 SPHEROMAK CONFIGURATION AFTER FORMATION AND THE TAYLOR STATE

5.1 2-D Magnetic Field Profiles

The MHD characteristics of spheromaks could be described conclusively if one could distribute numerous small magnetic probes all around inside the plasma. In actual experiment, however, these probes and their support system would probably degrade, if not destroy, the plasma. To measure the internal magnetic structure of the plasma, we employed the approach of scanning a one-dimensional probe array containing coils measuring all three components of the magnetic field. This technique relies upon the reproducibility of the discharges provided by the Figure-8 stabilization coils. Data from numerous discharges are compiled to construct one representative "average" discharge.

From these two-dimensional plots of the magnetic field structure, many of the quantities essential for characterizing the equilibrium can be calculated, including the poloidal flux Ψ , the poloidal current RB_θ , all three components of the current density j , the q profile, and the μ profile.

5.2 The q Profile

Radial profiles of q were obtained for the same set of discharges which corresponds to the flux plots shown above in Fig. 10. Figure 14 shows the time evolution of $q(R)$ profiles in the midplane. The q profiles can be determined accurately only for closed magnetic surfaces. A sudden change in the q profile is seen between 0.2 msec and 0.3 msec when the spheromak is forming. After the formation of the spheromak ($t \geq 0.3$ msec), the q profile remains unchanged in time and increases monotonically from the separatrix ($R = \pm 80$ cm) to $q_0 = 0.73$ at the magnetic axis ($R = \pm 60$ cm); this compares favorably with the q profile for the ideal spheromak [1].

5.3 Verification of the Taylor Minimum Energy State: μ Profile

Of fundamental importance to understanding the physics of spheromak equilibria is the concept of the Taylor minimum energy state. In this section, it is shown in detail that the measured magnetic structure of the S-1 Spheromak plasma in its equilibrium state after formation is close to the Taylor state.

The best way to determine how close this relaxed plasma is to the Taylor state is to measure the μ profile, where μ is defined by $\vec{j} \cdot \vec{B} / B^2$. If μ is constant in space, then the plasma is in the Taylor state.

Solving the axisymmetric Grad-Shafranov equation [32], it can be shown that

$$\mu = \frac{\vec{j} \cdot \vec{B}}{B^2} = I'(\psi) + \frac{p'(\psi)I(\psi)}{B^2}, \quad (5.1)$$

where $I(\psi) = RB_t$ is the poloidal current stream function, $p(\psi)$ is the

pressure, and the prime indicates differentiation with respect to ψ . In order for μ to be a spatial constant, the second term must vanish: Since its numerator is a function of ψ only, and the B^2 in the denominator is not in general a function of ψ only, the second term will not even be constant on a flux surface. Therefore, it cannot be constant in the whole plasma volume as required by the Taylor state. Therefore, the constancy of μ requires that $p'(\psi) = 0$. The equation remaining after dropping the p' term requires that I is a linear function of ψ in order that $I'(\psi)$ is constant. The slope of I vs. ψ is equal to the eigenvalue μ . For a given plasma shape, the eigenvalue is inversely proportional to the midplane separatrix radius.

The experimental results discussed below are for the same set of low temperature S-1 discharges as that presented in Fig. 10, wherein the plasma starts pinching off from the core at $t = 0.2$ msec and the formation is completed after $t = 0.4$ msec.

As a first check on whether the plasma is in a Taylor state at 0.5 msec, we examine a plot of I versus ψ as shown in Fig. 15 (multiple RB_{θ} - ψ curves), where $\psi = 0$ represents the symmetry axis of the configuration. As can be seen, the fit is indeed linear at $t = 0.5$ msec. This is not true during formation; at 0.2 msec, the slope of the $I(\psi)$ curve is 2.5 times greater near the magnetic axis than near the separatrix. This indicates that the plasma is far from the Taylor state initially.

Profiles of the μ parameter were obtained by measuring the local B inside the plasma with magnetic probes. In order to calculate μ , the current density must be calculated. The magnetic field data were first interpolated using a polynomial fit. This facilitates taking the curl of the fields to calculate the current density. The calculation assumes the symmetry axis of the plasma is unperturbed. The results of $\mu(R)$ in the midplane are shown in Fig. 16. At 0.2 msec, there is a deficit of current density near the symmetry

axis because the driving electric fields are strongest near the flux core. This is also reflected in the previously mentioned deviations of the $I(\psi)$ curve from linearity at this time. By 0.5 msec into the discharge, the current has diffused into the center to produce a flat μ profile. The straight horizontal line indicates the value of the slope of the I vs. ψ curve at this time. The value of 5.5 m^{-1} for the eigenvalue combined with the length to radius ratio of 0.53, determined from the flux plots in Fig. 10, imply a separatrix radius of 1.0 meters, based on the Taylor theory. This is in good agreement with the measured radius from the flux plot. Because of the limitations of the numerical differentiation, the calculation is valid to only $\pm 18\%$. The variation of the $t = 0.5$ msec curve from the expected value is within the error bars of the measurement.

Figure 17 presents a two-dimensional contour plot of μ across the plasma cross section. At early times, the μ profile peaks near the flux core and has a current hole near the symmetry axis. At 0.5 msec, the profile is basically flat throughout the plasma volume, with the gradients all occurring near the separatrix. The shaded areas are those that are within 15% of the nominal value of 5.5 m^{-1} .

An independent check of whether the plasma is in the Taylor state is the pressure gradient in the plasma. Evidence supporting the conclusion that the pressure gradient is near zero in the plasma interior has been obtained by using a triple Langmuir probe to measure the temperature and density as a function of time and space in the set of low temperature ($T_e \leq 30 \text{ eV}$) discharges discussed above. As the electron temperature increases ($T_e > 50 \text{ eV}$) with improvement of plasma conditions, a deviation of the plasma configuration from the Taylor state has been observed often, and will be described in Sec. 6 and Sec. 7.

6. RELAXATION PROCESSES IN THE S-1 SPHEROMAK PLASMA

6.1 Relaxation to the Taylor State: Global Observations

Taylor [16] showed that spheromak and RFP plasmas will relax toward a force-free state, $\vec{j} = \mu \vec{B}$, which corresponds to minimum potential energy subject only to the constraint that the global magnetic helicity K is conserved. K is the integral $\int \vec{A} \cdot \vec{B} dV$ over the entire plasma volume, $\vec{j}$ is the current density, and $\vec{B} = \vec{\nabla} \times \vec{A}$ is the magnetic field. The resulting force-free, minimum-energy Taylor state is such that μ is constant throughout the plasma volume. It is expected that a plasma has a tendency to approach this state through some energy dissipative processes.

A very important result from recent experimental spheromak research is the observation that plasmas tend to relax toward the force-free, minimum-energy Taylor state. The final plasma state is insensitive to initial conditions or details of the formation process so long as the geometry is not changed. Relaxation is an essential requirement for some inductive sustainment methods: The plasma is relied on to assimilate the fluxes injected into it to maintain adequately stable profiles.

Relaxation in S-1, and in spheromaks in general, was first evidenced by the plasma's maintenance of equilibrium profiles close to the lowest-energy, force-free eigenmodes predicted by theory [12-15]. In some cases, the applied coil currents in S-1 were expected to produce an equilibrium far from the Taylor state if the fluxes were transferred directly into the plasma. However, there was observed [21,23,24] to be a conversion of poloidal flux into toroidal flux or vice versa, depending on the applied currents, during formation. The data showed a final equilibrium near the Taylor configuration.

The Taylor state is characterized by the force-free condition $\vec{j} = \mu \vec{B}$, where μ is a constant independent of position. If μ is constant, μ also equals I/Φ by simple integration, where I is toroidal plasma current and Φ is

total toroidal magnetic flux in the plasma. Since μ experimentally is found to be a constant except near the plasma edge, I/Φ can be taken to be a representative μ value. The I/Φ ratio is proportional to the pinch parameter $q = 2I/a\langle B_\theta \rangle$ of RFP research through a simple geometric factor involving the plasma size. The time behavior of I/Φ in S-1 is shown in Fig. 18. S-1 plasmas adjusted themselves during formation so that the ratio I/Φ was a constant independent of initial conditions such as bank voltages; this ratio was maintained for the duration of a discharge as is shown in Fig. 18 for I and Φ measured with Rogowski coils and flux loops. If the plasma evolved after formation such that I/Φ deviated too far from a relatively narrow range, then relaxation oscillations restored I/Φ to the range that is theoretically predicted on the basis of a force-free, minimum-energy state. The theoretical value of $I(\text{MA})/\Phi(\text{Vsec}) = 3.58/r_0$, based on a classical spherical-boundary spheromak configuration where r_0 is the separatrix radius in meters, agrees well with the experiment taking $r_0 = 1.2$ m for the linked mode in the S-1 device. It should be noted that in some cases the final toroidal flux in the plasma could be greater than that injected from the flux core (Fig. 18, for example), giving clear evidence of flux conversion leading to a Taylor state.

Relaxation is a strong mechanism that produces a force-free, minimum-energy state even under extreme conditions [21]. An experiment was performed to test the limits of the plasma's ability to relax to a stable equilibrium under various initial conditions. Externally applied currents, that produce the poloidal and toroidal magnetic fields, were driven in an attempt to force the plasma away from the Taylor state during formation. It was found that both the toroidal plasma current I and the toroidal flux Φ varied in a similar fashion with a change in either one of the externally applied currents, as shown in Fig. 19. Relaxation by means of conversion of poloidal to toroidal or toroidal to poloidal magnetic flux was identified as having maintained the

proper magnetic flux distribution between the poloidal and toroidal fields so that the same I/Φ value was obtained under a wide range of initial conditions. The I/Φ results shown in Fig. 20 are computed from the I and Φ data of Fig. 19(a) and Fig. 19(b). (The nominal I/Φ values are lower here than in Fig. 18 because a different size and shape spheromak was created for this particular study.) It is clear that flux conversion can occur in both ways, from poloidal to toroidal and from toroidal to poloidal. Figure 21 shows the time evolution of the maximum value of the poloidal flux for two discharges for which the injected helicities, and resulting energy in the final spheromaks, are roughly the same. The difference between the two discharges is that in one case the available poloidal flux is larger than that needed for a Taylor state ($V_{TF}/V_{PF} = 6/6$) and in the other case the poloidal flux available to the plasma at initiation of discharge is too small for the final relaxed Taylor state ($V_{TF}/V_{PF} = 12/3$). This difference in initial poloidal flux ($t = 0.1$ msec) is evident in Fig. 21. In the former case the poloidal flux is observed to drop during formation. In the latter case, the flux is observed to increase, during formation ($t < 0.2$ msec), indicating toroidal to poloidal flux conversion. The evolution of the fluxes during the decay phase ($t = 0.2$ to $t = 0.4$ msec) is roughly the same in both cases although there were large differences in the initial conditions. To achieve the Taylor state, some process of relaxation must take place that involves reconnection of lines of force and conversion of poloidal to toroidal flux or vice versa.

The time evolution of both poloidal and toroidal flux, derived from flux plots, was studied during the formation phase [23]. There is a sudden (relative to the formation time) and sometimes large exchange of fluxes midway through the formation leading to the Taylor state. In Fig. 22, the poloidal flux (a) captured by the spheromak (poloidal flux at the magnetic axis) drops

precipitously during the same period that there is a large increase in the toroidal flux (ϕ) in the plasma. After formation, the fluxes are observed to decay slowly because of resistive losses.

The $q(\psi)$ profile ($= d\phi/d\psi$ obtained from flux plots) is initially zero when the plasma is just initiated since the field at $t = 0$ is purely poloidal. The evolution of $q(\psi)$ shows that it is relatively flat before formation of a spheromak ($t < 0.2$ msec) with a value on axis of $q_0 \sim 0.2$ at $t \approx 0.2$ msec. During flux conversion, q_0 rises and the profile changes to one which is an increasing function of ψ . After formation ($t > 0.4$ msec), $q(\psi)$ is a monotonically increasing function of ψ from the separatrix ($R = \pm 80$ cm) to $q_0 \approx 0.73$ at the magnetic axis ($R = \pm 60$ cm). This evolution of q_0 is coupled with the modes excited during relaxation (see Sec. 6.2).

6.2 Magnetic Fluctuations in S-1 Spheromak Plasmas During Formation

Large amplitude, globally coherent modes are observed [23] in coincidence with the flux conversion phenomena, suggesting that the modes play a vital role in the relaxation process by providing a means for flux conversion. These modes are low n -number ($2 \leq n \leq 5$), $m = 1$ modes where n and m are defined by the functional dependence $\exp[i(n\phi + m\theta)]$ of the fluctuations on toroidal angle ϕ and poloidal angle θ . During formation, peak amplitudes of the $n = 2, 3, 4$ modes relative to the unperturbed field have been observed as high as 20%, while more typical amplitudes are below 5%.

A significant finding is the temporal progression of the mode numbers through an $n = 5, 4, 3, 2$; $m = 1$ sequence during formation. This sequence coincides with q on axis, q_0 , rising through the integral fractions $q_0 = m/n = 1/n$ during formation (see Fig. 23). Once $q_0 > m/n$, the m/n rational surface is inside the plasma; the modes can then provide a means for relaxation since resistivity becomes important and magnetic field line reconnection can

occur. During a sequence, the n th mode usually is decaying while the $(n-1)$ th mode is growing. This simultaneous existence of several modes may provide for mode interaction which could then help the relaxation process proceed.

Well-defined modes are observed almost always during formation. B_R and B_θ data agree with respect to which modes are present and to their evolution, implying modes correspond to a helical deformation. Although amplitudes can be large, the $n > 1$ modes never directly cause a termination of the discharge. The modes always rotate in the $\vec{B}_{\text{poloidal}} \times \vec{v}_p$ (electron diamagnetic drift at the edge) direction. Fluctuation frequencies due to mode rotation range from 2 to 10 kHz and above. The m -number of the fluctuations was determined from the nineteen-channel ultra-soft (> 10 eV) x-ray detection system.

6.3 Plasma Relaxation During the Decay Phase in High T_e Plasmas

After glow discharge cleaning and with an increasing number of spheromak discharges, the plasma becomes cleaner and the magnetic activity during the decay phase is observed to increase and the relaxation oscillations become pronounced. Recent high T_e operation has allowed us to obtain a comprehensive picture of the sawtooth-type relaxation event [33]. During the decaying phase of hot spheromaks, up to three relaxation events were observed. By adjusting plasma parameters, one relaxation event was made reproducible over many discharges.

Figure 24 shows a time evolution of T_e profile measured by the multipoint Thomson scattering system. The radial axis is defined by the distance along the laser beam path from the point where the beam crosses the midplane ($z = 0$, $R = 47$ cm). Since the magnetic probe was inserted at the same time to monitor the magnetic profile in this experiment, the electron temperature was reduced by 30%. After the formation of the spheromak, the T_e

profile gradually changes to a peaked profile up to 360 μsec . The maximum peak temperature ($T_e = 75 \text{ eV}$) is obtained at 360 μsec when the peaking of T_e becomes maximum; afterwards, a large drop in T_e is observed and the T_e profile changes from peaked to broad. Figure 25 shows the radial profiles of the poloidal and toroidal magnetic fields on the midplane as a function of time, which were obtained from the magnetic probe array measurement. The poloidal and toroidal magnetic field profiles gradually become more peaked as time increases to 360 μsec . After this time, the profiles broaden again. Based on $\vec{\nabla} \times \vec{B} = \mu_0 \vec{j}$, this peaking and broadening indicates that the toroidal current (j_t) keeps peaking until $t \sim 360 \text{ } \mu\text{sec}$, after which some redistribution restores a broad profile. The j_t profile is expected to be similar to that for B_t assuming nearly constant $\lambda (= j_t/B_t)$ profile.

The poloidal flux Ψ , toroidal flux Φ and q_0 are shown in Fig. 26 with respect to time. Initially, at about 300 μsec , Ψ/Φ is about 2.7 and the q value at the magnetic axis is 0.5, which are expected values for the Taylor state. In the peaking phase, from 300 μsec to 360 μsec , Ψ/Φ increases and q_0 decreases to 0.35 which indicates that the spheromak becomes poloidal-flux-rich and deviates from the Taylor state. The $\dot{\Psi}/\Psi - \dot{\Phi}/\Phi$ curve shows a preferential decay of Φ over Ψ until 360 μsec after which the relaxation occurs. Once the spheromak begins to relax from 360 μsec , Ψ/Φ drops to 3.0 and q_0 value comes back to 0.5. The $\dot{\Psi}/\Psi - \dot{\Phi}/\Phi$ curve reverses its sign during the relaxation from 360 μsec to 390 μsec , which suggests flux conversion from poloidal flux to toroidal flux ($\dot{\Psi} < 0$, $\dot{\Phi} > 0$). The flux conversion brings the spheromak from the non-Taylor state with excessive poloidal flux to the Taylor state.

According to the result of toroidal mode analysis using external pick-up coils which are located at $z = 60 \text{ cm}$ with equal toroidal distances [23], the $n = 2$, $m = 1$ mode starts growing just before the onset of the relaxation and

becomes dominant during the relaxation. In the two-dimensional flux contour made experimentally, the flux contour elongates during the relaxation and comes back to the original oblate-shape symmetric state after the relaxation. These behaviors suggest that the $n = 2, m = 1$ kink mode may play an important role in the flux conversion as conceived in Sgro's MHD simulation [34].

In order to investigate transport under the best conditions, the T_e profile was measured after the magnetic probe was removed from the plasma. Figure 26(e) shows the time evolution of peak plasma temperature without the probe in the plasma. A maximum temperature of over 100 eV is obtained at about 350 μ sec, just before the onset of relaxation. Figure 26(f) shows the energy confinement time for the inner region of the plasma, τ_E , as calculated from

$$\tau_E = \frac{3/2 \langle n_e T_e + n_i T_i \rangle}{n(T_e) \langle j^2 \rangle - 3/2 (\partial \langle n_e T_e + n_i T_i \rangle / \partial t)} \quad (6.1)$$

where the brackets denote an average over the region defined by $\psi > 0.7\psi_{\max}$. $n(T_e)$ is the plasma resistivity, which includes the anomaly factor Z_{anom} . The value of Z_{anom} has not been measured, but is generally in the range of 2 - 10 for most operation conditions of RFP [35] and spheromak [36] devices. Based on $j/n_e = 5 \times 10^{-14}$ A·m², Z_{anom} is estimated to be 5 with 50% error. The thermal energies of the electrons and ions are assumed to be equal. Under these assumptions, τ_E is calculated to have a maximum value of over 70 μ sec in the middle of the peaking phase and decreases by a factor of five during relaxation. Although various reasons can be suggested to explain the degradation of the confinement, magnetic reconnection phenomena are considered to be most responsible.

Without the relaxation oscillation present, the $n \geq 2$ global modes are no longer as prevalent, and amplitudes are usually less than 2%. However, in addition to the above-described modes, fluctuations are usually present which are locally but not globally coherent in ϕ with frequencies on the order of 10 to 70 kHz. Amplitudes of these high-frequency fluctuations are also on the order of $\tilde{B}/B \leq 5\%$. These fluctuations seem to be correlated over toroidal angles of 100° or less. High-frequency fluctuations are also observed in other local measurements such as electron density, measured with Langmuir probes, and in line-integrated measurements such as ultrasoft x-ray. These spatially localized fluctuations may be high n -number "modes" which do not have global coherence because of the interaction of a large number of modes and the high shear on the edge of the plasma.

7. CONFINEMENT CHARACTERISTICS OF THE S-1 SPHEROMAK

In the S-1 device, spheromak plasmas with internal fields greater than 3 kG have been generated with toroidal plasma currents up to 550 kA. As discussed earlier, the configuration lifetime has exceeded 1 msec, with a magnetic field decay time $\tau_B = B(dB/dt)^{-1}$ ranging from 0.5 msec to 2 msec. In this section we focus our attention on the confinement of S-1 Spheromak plasmas. Scaling characteristics of the electron temperature and density and total beta value are studied with respect to the most important heating source, the ohmic heating current density, together with the effects of impurities. Most importantly, it is found that the peak electron pressure scales as $n_{eo}T_{eo} \propto j_0^2$, where j_0 is the toroidal current density of the inner core plasma. These results are analyzed in terms of a simple power balance code. Furthermore, the energy confinement time has been determined based on

the power balance of the S-1 spheromak. The data discussed in this section were all obtained with the stabilizing coils or funnel-shaped conductors, unless otherwise noted.

7.1 Line-Averaged Density

Line-averaged electron density $\int n_e dl$ was measured with a CO_2 laser interferometer to help determine the particle loss rate. Before Figure-8 coils were installed, the density increased in a very uneven manner until 0.6 msec (line-linked case) after which it decayed immediately. After Figure-8 coils were installed, the density ramped up to its peak at 0.2 msec and decayed slowly until ~1 msec. With the addition of funnel-shaped stabilizer panels, a sharp line-averaged density loss was observed during formation of the spheromak plasma ($t = 0$ to 0.25 msec), after which $\int n_e dl$ stayed constant. A typical evolution of the line-averaged density of the plasma measured at $R = 45$ cm is shown as average density in Fig. 27.

The line-averaged density was observed to scale linearly with filling pressure (equivalent to 80% ionization) up to 4 mtorr. Beyond that point, density increased more slowly. Also, the line-averaged density was observed to increase linearly with poloidal and toroidal current, while central electron density remained constant. This suggests that the plasma density of the outer edge plasma increases with current, as long as we assume the plasma size is constant.

7.2 Assessment of Impurity Effects Using Optical Diagnostics

Emission from low-Z impurity ions and metallic impurities, such as NiII, CuII, TaII, and FeII, has been observed in the visible region. The dependence of line intensity on operational parameters, such as equilibrium field shape, neutral gas pressure, and bank voltage, has been studied. The most important

result is the significant reduction of iron and nickel emission after installation of the Figure-8 coils, as has already been shown in Fig. 13, which indicates reduced interaction between the plasma and the vacuum vessel walls and flux core.

The Lyman δ , CII - CIV, and OII - OVI lines in the VUV region were identified with the GISMO system, a double line VUV spectrometer. Figure 28 shows a time evolution of OIV (790 Å) and OVI (1032 Å) emission intensity together with total toroidal current for typical discharges. Although CV and OVII lines should be detected, they were not observed because of the limited wavelength range of the system. The density of these impurity ions is estimated assuming that all the plasma parameters are radially uniform. The carbon ion density is calculated to be $\sim 3 \times 10^{11}/\text{cm}^3$, while the oxygen ion density is $(6.0 - 12) \times 10^{11}/\text{cm}^3$ in the best condition.

The particle confinement time of oxygen ions can be estimated by studying the time evolution of the line radiation intensities based on a simple zero-dimensional code. Experimental data of electron density and temperature were input into the rate equations with various confinement times. The time history of the intensity of the OIII line through OVI line thus calculated agreed well with the observed ones. It was found that in the present temperature range, the ratio of the peak intensity of the OVI line to that of the OV line is quite sensitive to the confinement time included in the rate equation. A 15% uncertainty in the T_e measurement leads to confinement times ranging from 0.1 to 0.5 msec.

7.3 Radiated Power

Results from the bolometer for a typical 200 kA discharge with $\bar{n}_e = 5 \times 10^{13} \text{ cm}^{-3}$ indicated a radiated energy of about $7 \times 10^{-3} \text{ J/cm}^3$. Assuming isotropic emission, the total radiated energy was about 6.3 kJ. This

was nearly 50% of the magnetic energy in the plasma assuming that the average toroidal and poloidal fields were 1.5 kG and the plasma volume was 0.9 m^3 . Considering a discharge of 1-msec duration, the $7\text{W}/\text{cm}^3$ agrees with a simulation code.

It was concluded that in a typical plasma discharge of $T_e \leq 50 \text{ eV}$ and $n_e \geq 5 \times 10^{13} \text{ cm}^{-3}$ with -2 - 3% low-Z impurity ions, radiated power loss plays a very important role (>50%). However, for higher T_e regime, other loss mechanisms (convection and conduction) can become more important.

7.4 Ultra-Soft x-ray Imaging Diagnostics

Initial results at low electron temperature indicate a flat or inverted radial emissivity profile — typical of low energy radiation. By comparing discharges with various filters, the primary radiative energy contribution was found to be from 6.4 to 11.2 eV, most probably Lyman alpha.

During the runs in which Thomson scattering measured high electron temperatures, this ultra-soft x-ray system measured significant emission with the 200 eV high pass filter. By using a MgF_2 filter to estimate the radiative emission in the visible, near UV and near IR spectra, the sensitivity of the detectors to (and the leakage of the filters from) low energy emission was assessed to be small.

7.5 Electron Temperature T_e and Density n_e and Their Scaling Characteristics

For optimized plasma discharges with Figure-8 coils, the average electron temperature was 50-70 eV. The electron temperatures measured initially by a single-point Thomson scattering system for plasma discharges with the Figure-8 coils had relatively large scatter in distribution, which was attributed to low photon counting statistics as well as discharge-to-discharge plasma variations [37]. These measurements have been

confirmed by the multipoint Thomson scattering system with better photon statistics. The multipoint Thomson scattering system generated more reliable and reproducible sets of data for electron temperature and density [38]. The local electron density ranges from $2 \times 10^{13} \text{ cm}^{-3}$ to $1 \times 10^{14} \text{ cm}^{-3}$, depending primarily on the neutral gas fill pressure. For discharges with the highest values of T_e , the density was in the range of 3 to $6 \times 10^{13} \text{ cm}^{-3}$.

The time evolution of the profile of electron temperature obtained with the multipoint Thomson scattering system was already shown in Fig. 24. The peak (maximum along profile) electron temperature occurs in the central region of the plasma. The time evolution of the peak T_e and the electron density n_e measured at the position of peak T_e are shown in Fig. 29 for a discharge exhibiting a relaxation event. For the data shown in Fig. 29, the spheromak starts pinching off from the flux core at $t = 170 \text{ } \mu\text{sec}$, is completely pinched off from the flux core at $t = 290 \text{ } \mu\text{sec}$, and then goes through a peaking and relaxation cycle as mentioned in Sec. 6. The electron density profile stays relatively flat with its average value remaining constant throughout most of the discharge. Because relaxation events usually reduce the temperature, the data used for scaling is representative of the parameters before relaxation events in discharges which exhibit such events.

Figure 30 shows the peak electron temperature versus density obtained over many discharges for a constant plasma current. It is observed generally that $n_e T_e$ is constant for a constant discharge current density j and that $n_e T_e$ increases with I .

For a series of ~150 discharges, the bank voltage was gradually increased together with the equilibrium field so that the magnetic axis position and plasma minor radius were kept constant. This keeps the current and current density proportional to the bank voltage, so the temperature and density can be scaled relative to the current density. For various types of

discharges in S-1, the current density j is not uniquely determined by the total current I because of the differences in size (R and a) and shape of the plasma cross section. Since the plasma is heated solely by ohmic heating currents, local current density is the most important factor determining the peak electron temperature. In the present scaling analysis, current density j was chosen as the independent variable.

Figures 31, 32, and 33 show the peak electron temperature T_{eo} , density n_{eo} , and pressure $n_{eo}T_{eo}$ averaged over several discharges at each bank voltage, versus peak toroidal current density j_o of the plasma core region. The peak electron temperature increases with increased plasma current as $T_{eo} = j_o^{1.8}$, while the electron density shows little change with j_o . The resultant electron pressure p_{eo} ($= n_{eo}T_{eo}$) increases as $p_{eo} = j_o^2$. From a least-squares fit to the pressure data obtained in a one-day experiment, it is found that $n_{eo}T_{eo} = j_o^\alpha$ or $T_{eo} = j_o^\alpha/n_{eo}$, with $\alpha = 1.9 \pm 0.4$. The current density is proportional to the poloidal magnetic field, so that $p_{eo} = \beta_p^2$ for a constant plasma cross section. With $T_i = T_e$ assumed, this leads to a constant poloidal beta over the range measured.

These results along with data from other diagnostics have been used in a zero-D model to study numerically the power balance in S-1. The zero-D code makes an estimate of impurity radiation based on a time-dependent coronal model by determining the charge state evolution of the carbon and oxygen impurities. Input to the code are the electron density and current density time evolution as well as the estimated particle confinement time, and impurity fractions of oxygen and carbon. The code then computes the time evolution of the electron temperature and the power losses due to radiation, conduction, and convection estimated by a simple model. Scaling results of the electron temperature with plasma current density from the code have been compared with the Thomson scattering measurements and are in good agreement

with the j^2/n_e scaling. The power loss from the plasma at low temperatures is predominantly from radiation. In this model at the higher temperatures ($T_e \approx 70$ eV), the loss from radiation and convection become comparable. However, the present 0-D simulation cannot determine the main confinement characteristics since more sophisticated models (1D - 2D) are needed to explain the present transport data.

To elucidate the confinement features of ohmically heated plasmas, such as the S-1 spheromak, the dependence of the plasma pressure on the magnetic field strength is often checked. Figure 34 depicts the measured electron pressure of the plasma core region with respect to peak toroidal magnetic field B_{to} . It was found [39] that $n_{eo}T_{eo}$ is proportional to B_{to}^2 and the optimum plasma beta is between 8 and 10%, assuming $T_{eo} = T_{io}$. (In low q pinch plasmas [such as spheromaks and RFP's], T_i is sometimes measured to be higher than T_e). If the data points from various RFP devices such as OHTE [40], ZT-40M [41], and TPE-1RM [42] are plotted in this figure, they reside in the shaded region. The agreement of the trend of S-1 data with that of RFP devices suggests that common physics mechanisms might be determining the maximum beta value. It should be noted that relaxation phenomena as described in Sec. 6.3 are also observed in high T_e RFP discharges.

7.6 Energy Confinement Time τ_E^* of the Inner Plasma Core

The energy confinement time of the S-1 spheromak plasma can be determined by monitoring power input (through joule heating) and the time evolution of the profiles of the electron temperature and density. Generally, it was observed that the global confinement time, which was determined by the total input power and the global loss, was shorter than the central confinement, which was calculated by estimating the power balance (within a factor of $\approx 2 - 3$) in the plasma core region. An example of τ_E^* measurements

defined at the core of the plasma was shown in Sec. 6.4. Due to both the large fluctuations and the low electron temperature observed at the plasma edge, and based on experimental evidence of a fast decay rate of edge poloidal current, energy loss is expected to occur predominantly at the plasma edge. Experimentally, this hypothesis has been verified in RFP & other spheromak devices. In addition, the edge region of the S-1 spheromak plasma cannot be measured well, and τ_E is better defined in the central plasma region near the magnetic axis.

The confinement time of the central plasma region is defined by

$$\frac{3/2}{dt} \frac{d\langle n_e T_e + n_i T_i \rangle_0}{dt} = \eta j_0^2 - \frac{3/2 \langle n_e T_e + n_i T_i \rangle_0}{\tau_E^*} \quad (7.1)$$

where the brackets $\langle \rangle$ denote averages over the region defined by $\psi > 0.7\psi_{\max}$. Although the ion temperature T_i is usually found to be higher than T_e in similar discharges, we assume $T_e = T_i$ to simplify the analysis. The ohmic input power is determined based on $\eta = Z_{\text{anom}} \eta_{\text{classical}}$. The local value of Z_{anom} cannot be determined in the present experiment due to the difficulty in measuring the one-turn loop voltage. Generally, it is in the range of $\approx 2 - 15$ for spheromaks and RFPs. Based on the measured values of $j_0/n_{e0} = (4 - 6) \times 10^{-14} \text{ A} \cdot \text{m}^2$, Z_{anom} is estimated to be $\approx 3.5 - 5$. If these values are used in Eq. (7.1), τ_E^* ranges from 50 to 100 μsec . It should be noted that this number is an upper estimate of the energy confinement time.

To calculate the global confinement time of the plasma, the decay rate of the magnetic energy dW_B/dt is often used. Usually the global confinement time is $\approx 2 - 3$ times smaller than the confinement time of the inner core region.

7.7 Measurement of Particle Confinement Time

To estimate the confinement features of the S-1 Spheromak we have measured the local perpendicular transport coefficient of injected impurity ions, $D_{\perp}$. There are many means of attempting such a measurement. Many of the previously proposed schemes result in measurements which either produce a global value of τ_p or require plasma features inconsistent with S-1 parameters. Therefore, the method chosen for S-1 is similar to that of Levinton and Meyerhofer [43] in which a carbon impurity is injected in a narrow location near the magnetic axis of the plasma using graphite tips attached to a stainless steel rod. Following the impurity transport spectroscopically then provides a direct measure of the local particle diffusion coefficient.

Although the injection scheme is quite similar to previous work on Proto S-1/C, the method of analysis is quite different. In the case of S-1, the impurity transport is influenced quite strongly by ionization, especially at high electron temperatures (i.e., $20 \text{ eV} \leq T_e \leq 70 \text{ eV}$). The radial extent of the carbon emission is determined by a balance of ionization and particle diffusion. Thus, by measuring the radial emission profile, one can deduce the carbon diffusion coefficient. In addition, it was found experimentally that carbon could be injected in a quasi-steady-state manner by blow off from the graphite tips due to the large plasma current near the probe. In the previous work, injection was only possible by introducing a discharge between two graphite tips in the plasma. The quasi-steady-state injection allowed for a simplified analysis and eliminated the need to follow the emission temporally. In addition, a multichord optical array enabled one to obtain a full radial profile on a single discharge. This analysis has been compared to, and checked by, the time dependent case at low temperatures.

The line predominantly observed because of its strong emission was the 4267Å line of CII. A diffusion coefficient may be determined on a single discharge if T_e and n_e are known locally. However, since the ionization rates are strong functions of T_e and n_e , averaging over many discharges has proven more reliable. Similar experiments have been repeated for many different plasma conditions in which T_e varies from 8 - 65 eV, n_e varies from $5 - 10 \times 10^{13} \text{ cm}^{-3}$, and B varies from 1 - 2.5 kG. The (modest) range of plasma parameters allows for an attempt at determining the scaling of $D_{\perp}$. The preliminary indication is that $D_{\perp}$ is independent of n_e , scales approximately linearly with T_e , and approximately inversely with B . In Fig. 35, the diffusion coefficient $D_{\perp}$ is plotted against its exponential dependences on T_e and B from a regression analysis. The "Bohm" like diffusion behavior is consistent with the results found earlier [43] on the Proto S-1/C experiment. Making the reasonable assumption of ~10 cm for the density scale length, values of τ_p ranging from 100 μs to 600 μs are found.

8. SUMMARY AND CONSIDERATIONS FOR FUTURE RESEARCH

Together with the advances in tokamak research, there has been a steady rise in the performance of alternate concepts aiming for potentially superior reactor options. The principal direction in which a truly significant fusion-reactor improvement can still be made is in regard to basic reactor-plasma geometry. One promising option is the "spheromak" — a member of the "compact-torus" class of toroidal plasma configurations which do not require the magnet coils or vacuum vessel to link the plasma, thus allowing the possibility of a smaller and less expensive reactor core.

In the spheromak concept, a high-beta toroidal plasma is stabilized by a self-generated toroidal field. The S-1 Spheromak, which was completed in 1983, has successfully demonstrated a "slow" inductive spheromak-formation

technique, which involves transferring and reconnecting magnetic fields from a "flux core" situated on the large-R side of the plasma. The S-1 device has also shown how "Figure-8" coils and other passive stabilizers can suppress the tilting and shifting modes — the most dangerous MHD instabilities. Another important finding is identification of flux conversion between the toroidal and poloidal fluxes of the spheromak during and after the formation of the plasma. The correlation between the MHD mode behavior and the Taylor relaxation process has been described.

The recent S-1 experiment has successfully carried out the confinement study of spheromak plasmas, with an improved machine geometry. Gross MHD stability was maintained by a set of the Figure-8 coils and funnel-shaped passive conductors which permitted the production and study of completely detached spheromak plasmas. The most significant finding is that the peak electron pressure $n_{eo}T_{eo}$ scales with j_o^2 , where j_o is the current density of plasma inner core. In most discharges, $T_{eo} \propto j_o^2$ with $n_{eo} \approx \text{constant}$. It should be noted that the electron pressure of the S-1 device and RFP devices follow the same empirical scaling with similar values of optimum beta (8 - 10%). Estimates of energy confinement time have been made. The S-1 spheromak has $n_e t_E$ values of up to $10^{10} \text{cm}^{-3} \text{sec}$ and T_e values in excess of 100 eV, although these parameters are not attained simultaneously. A comparison of the experimental data and a simple power balance code suggested that the plasma overcomes the low-Z radiation barrier which plagued early experiments.

In the high temperature plasmas, a "sawtooth-type" relaxation cycle was observed both in the magnetic configuration and electron temperature profile. It was found that the confinement characteristics of the spheromak significantly affected, and were significantly affected by, the relaxation

phenomena. In order to make spheromak a viable candidate for a fusion reactor, it is essential to avoid the catastrophic sawtooth crashes by controlling the magnetic configuration and the plasma pressure profile.

The extension of the S-1 operation to higher current density is a goal for the future operation of S-1 and for some other experiments. A compression experiment on S-1 is being carried out to obtain higher current densities and higher temperature plasmas [44].

A further upgrade of the S-1 device which uses a current transformer has been proposed also. There has been increasingly clear experimental documentation of a dynamo process that could be used to enhance the toroidal flux of the spheromak by conversion of poloidal flux created by increasing the toroidal current. This spontaneous relaxation mechanism, which was not anticipated at the onset of spheromak research, has the potential for a major enhancement of the effectiveness of inductive spheromak formation. The combination of the new flux core with a modest transformer system should allow the predicted dynamo process to maintain the plasma for a much longer period with larger current capability.

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FIGURE CAPTIONS

FIG. 1(a). Classic spheromak configuration.

FIG. 1(b). Oblate spheromak configuration with current hole. Dotted-region indicates no current.

FIG. 2. Cross section of S-1 device showing vacuum vessel, EF coils, flux core, and plasma.

FIG. 3. The S-1 Device.

FIG. 4. Flux core mounted in the vacuum vessel center section.

FIG. 5. Schematic depiction of major S-1 diagnostics.

FIG. 6. Inductive spheromak formation.

FIG. 7. Typical midplane profiles of the spheromak's poloidal and toroidal magnetic fields as a function of time for a discharge lasting over 0.7 msec.

FIG. 8. Perspective view of passive Figure-8 coil stabilization system and the S-1 flux core.

FIG. 9. Evolution of radial profile of internal magnetic fields taken between 0.3 msec and 0.6 msec after initiation of discharges

(curves 1-7 are taken every 0.05 msec interval during this time). (a) and (b) refer to toroidal (B_t) and poloidal (B_z) field in the absence of Figure-8 coils and (c), (d) to B_t , B_z with the Figure-8 coils installed.

FIG. 10. Time evolution of poloidal flux contours Ψ and poloidal current contours RB_t obtained from magnetic probes inside the plasma from 40 consecutive and reproducible shots. The separatrix of the spheromak is shown by the outermost Ψ contour.

FIG. 11. Cross section of S-1 device showing funnels installed.

FIG. 12. Poloidal flux contours with funnels installed.

FIG. 13. Comparison of S-1 data before (left-hand side) and after (right-hand side) installation of the Figure-8 coils, showing significant improvements in impurity line intensities. Ordinates are in arbitrary units.

FIG. 14. Radial midplane q profiles versus time.

FIG. 15. Measurements of $I(\Psi) = RB_\phi$ versus Ψ for four times during a discharge. The slope of this curve is expected to be equal to μ in the Taylor State.

FIG. 16. Plots of $\mu = \mu_0 \int \cdot B/B^2$ across the midplane of the S-1 device during the formation phase ($t = 0.2$ msec) and after the

equilibrium is established ($t = 0.5$ msec). The horizontal solid line is the expected value of μ based on the slope in Fig. 15.

FIG. 17. 2-D contour plots, during (0.2 msec) and after (0.5 msec) formation, of (a) poloidal flux (increments are 10 mWb), and (b) $\mu = \mu_0 j \cdot B/B^2$. The shaded area is the region in which μ is within $\pm 15\%$ of the nominal value of 5.5 m^{-1} .

FIG. 18 Time evolution of poloidal (top) and toroidal (center) fluxes and ratio of toroidal plasma current to toroidal flux (bottom) in long-lived linked discharge. ψ^{core} is the total poloidal flux linking the core. The toroidal flux in the formed plasma is 40% greater than that originally in the core. The ratio of toroidal plasma current to toroidal magnetic flux in the plasma, I/Φ , is nearly constant even though, individually, I and Φ vary dramatically. The nominal value of I/Φ agrees with the theoretical value of μ based on an oblate spheromak with a midplane separatrix radius of 1.2m. The dashed line shows I/Φ from a different discharge which exhibits multiple relaxation events. In this latter case, I/Φ shows small excursions but still remains close to a nominal value.

FIG. 19. Evidence of flux conversion in spheromak formation. Both toroidal plasma current (poloidal flux) and toroidal magnetic flux in the plasma increase with either the poloidal-field bank voltage V_{PF} or the toroidal-field bank voltage V_{TF} .

(a) If V_{PF} (toroidal current in the flux core) is increased with V_{TF} (toroidal flux in the flux core) fixed, both I (toroidal

plasma current) (top) and Φ (toroidal flux in the plasma) (bottom) increase.

(b) If V_{TF} (toroidal flux in the plasma) is increased with V_{PF} (toroidal current in the flux core) fixed, both Φ (toroidal flux in the plasma) (top) and I (toroidal plasma current) (bottom) increase.

FIG. 20. I/Φ of the spheromak equilibrium after formation versus bank voltage. I/Φ is equivalent to an average μ over the cross section ($j = \mu B$). I/Φ is independent of the initial conditions.

FIG. 21. Maximum poloidal flux for an initially poloidal-flux-rich case ($V_{TF}/V_{PF} = 6/6$) and an initially toroidal-flux-rich case ($V_{TF}/V_{PF} = 1/3$). A conversion of poloidal to toroidal and toroidal to poloidal flux, respectively, occurs during the formation phase ($t = 0. - 0.2$).

FIG. 22. Time evolution of (a) poloidal flux Ψ_{max} , (b) toroidal flux Φ , and (c) q on axis, q_0 . There is a precipitous drop in Ψ_{max} and a concurrent sudden and large increase in Φ during mode activity.

FIG. 23. Mode amplitude vs time showing a clear $n = 3, 2$ sequence. Formation is completed at 0.4 msec, and the discharge terminates at 0.75 msec. The toroidal dependence of B_R is shown with respect to the axisymmetric $n = 0$ component (circles). PF (TF) denotes poloidal (toroidal) flux.

- FIG. 24 Time evolution of $T_e(r)$ measured by multipoint Thomson scattering system. $r = 0$ is defined by the point where the laser beam crosses the midplane ($R = 42$, $z = 0$).
- FIG. 25. Radial B_p and B_t profiles in the midplane versus time.
- FIG. 26. Evolution of key plasma parameters during the relaxation event.
- FIG. 27. A typical evolution of the line-averaged density versus time. We expect a central electron density of $(5 - 10) \times 10^{13} \text{ cm}^{-3}$ for $0.3 \leq t \leq 0.9 \text{ msec}$.
- FIG. 28. Time evolution of a) OIV (790Å) and b) OVI (1032Å) emission intensity, and c) toroidal plasma current for the same one discharge.
- FIG. 29. Peak electron temperature and density measured in many reproducible shots versus time.
- FIG. 30 T_e versus n_e of the plasma core region for constant plasma current discharges ($I = \text{constant}$, $j = \text{constant}$).
- FIG. 31. Peak electron temperature T_{e0} versus current density j_0 of the plasma core region (at position of peak electron temperature).
- FIG. 32. Electron density versus current density j_0 of the plasma core region.

FIG. 33 Electron pressure versus current density j_0 of the plasma core region.

FIG. 34. Scaling of electron pressure versus magnetic field at the plasma core. Data suggests $n_{e0}T_{e0} \propto B_0^2$; shaded region shows data obtained in primary RFP devices (OHTE, ZT-40M AND TPE-1RM).

FIG. 35. The perpendicular particle diffusion coefficient $D_\perp$ vs. its exponential dependences on T_e and B obtained from regression analysis. All data points represent measurements made after full pinchoff but before relaxation ($t \leq 370 \mu\text{sec}$).

Fig. 1(a)

#88X0357

Fig. 1(b)

81X0329

Fig. 2

Fig. 3

Fig. 4

87X0279

Fig. 5

QUASISTATIC FORMATION USING INDUCTION

Fig. 6

#84X0371

Fig. 7

84X1155

COIL SYSTEM & S-I FLUX-CORE

Fig. 9

Fig. 10

85X0044

Fig. 11

88X0319

Fig. 12

Fig. 13

Fig. 14

Fig. 15

Fig. 16

Fig. 17

Fig. 18 (cont. on 1-1, 7)

#88X0227

Fig. 18

Fig. 19(a)

Fig. 19(b)

86X1104

#87X0239

Fig. 21

Fig. 22

Fig. 23

87X0555

#87X0980

Fig. 25

Fig. 26

Fig. 27

Fig. 28

Fig. 29

Fig. 30

Fig. 31

Fig. 32

#88X0225

Fig. 33

#87X0976

Fig. 34

92

Fig. 35

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